E-24-669

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	Oct. 17, 1995	Final 2/1/89 - 6/30/95

4. TITLE AND SUBTITLE

5. FUNDING NUMBERS

6. AUTHOR(S)
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES COR:

12a. DISTRIBUTION/AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A
Approved for public release
Distribution Unlimited

12b. DISTRIBUTION CODE

19970227 072

13. ABSTRACT (Maximum 200 words)

We have identified an important class of intermodal network design problems where we can prove that the submodular property holds. This class includes the intermodal channel selection problem as well as the terminal selection problem for one directional flow. We have just completed computation testing on multi-facility location problems to compare this methodology with commercial integer programming codes and are preparing this work for publication. This work was presented as a "focus paper" at TRISTAN II in Capri, Italy in June 1994. The algorithm has been embedded as a tool in the CAPS Logistics Toolkit and is used by a number of commercial companies to locate facilities.

14. SUBJECT TERMS			15. NUMBER OF PAGES 6
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT

FINAL REPORT ON ONR CONTRACT N00014-89-J-1571

H. D. Ratliff J. J. Bartholdi, III

October 17, 1995

1 Submodular set functions in intermodal network design

We have identified an important class of intermodal network design problems where we can prove that the submodular property holds. This class includes the intermodal channel selection problem as well as the terminal selection problem for one directional flow. When used in conjunction with a binomial search tree, the submodular popery allows us to significantly reduce, compared to using traditional integer programming based methods, the set of solutions that have to be examined. It also allows us to say more about the best solution obtained if the search is stopped prematurely. Knowing that the submodular property holds also allows the use of a class of heuristics with nicer theoretical properties than is normally possible. We have just completed computation testing on multi-facility location problems to compare this methodology with commercial integer programming codes and are preparing this work for publication. This work was presented as a "focus paper" at TRISTAN II in Capri, Italy in June 1994. The algorithm has been embedded as a tool in the CAPS Logistics Toolkit and is used by a number of commercial companies to locate facilities.

2 Geometric searching based on spacefilling curves

We have looked at how to embed additional information in geocodes so that a geographic information system can support not just standard database queries, but queries that are particular to logistics planning. We are working on two papers and have had one, "Robust spatial searching with spacefilling curves", presented at the 6th International Symposium on Spatial Data Handling, Edinburgh, Scotland during September, 1994.

With new Ph.D. student Paul Goldsman we have extended these results to create a method by which any triangulated surface may be continuously indexed. This includes topographic surfaces, such as produced by satellite photographs, as well as 3-dimensional earth models, such as globes.

Our ideas here have been embedded in several commercial products, including ARC/INFO, one of the premier geographic information systems.

3 Freight handling terminals

With Ph.D. student K. Gue we studied the design and operation of freight handling terminals in the less-than-truckload (LTL) motor carrier industry. Our primary task is to determine how to improve terminal throughput by careful design and layout. For example, what shape should a terminal be? What sort of material handling system should be installed inside the terminal? How should trailers be assigned to terminal doors?

To address these questions we have built models to measure the impact of design changes on system throughput. Our models consider the assignment of trailers to doors, material handling systems, congestion, and freight mix.

Industry interaction has been a cornerstone of our research. We have developed an excellent working relationship with Carolina Freight Carriers and with Roadway and are currently testing our models at their Atlanta facilities. We have visited terminals and corporate headquarters of several major LTL motor carriers during the last two years, including:

- Carolina Freight Carriers
  - Corporate HQ and breakbulk terminal in Cherryville, NC (Nov 92, Apr 93)
  - Satellite terminal in Douglasville, GA (Spring 93)
  - Breakbulk terminal in Atlanta, GA (at least monthly since Jan 93)
- Roadway Express
  - Automated breakbulk in Kernersville, NC (Dec 93)
  - Breakbulk in Atlanta, GA (Fall 93)
  - RPS small package terminal in Atlanta, GA (Fall 93)
- Southeastern Freight Lines
  - Corporate HQ and terminal in Columbia, SC (Feb 94)
  - Terminal in Atlanta, GA (Oct 93, Apr 94)
- TNT Express; terminal in London, UK (May 94)
- American President Lines; Intermodal terminal in Atlanta, GA (Winter 93)

We have continued to work with Roadway and recently helped layout their Atlanta facility. Our experience there confirms predictions of our model that five to ten percent savings in labor is possible when doors are assigned to account for material flow.

4 Shipment planning

For large international shipment planning problems such as those faced by the US military, as well as large US private shippers, there is a fundamental problem in defining the shipping network so that analysis is possible. The shipping network may be imagined to be composed of two pieces: a geographical network (for example, ports, sea lanes, rail terminals, rail track, etc.), and a time network (for example, the schedules for the ships and trains). Unfortunately, any practical problem becomes immense when viewed as a "time-expanded" network. We are examining both what elements of the network that must be captured and how to store and manipulate the network in order to optimize shipment planning.

To better understand the these issues we have visited ports and terminals of several major carriers during the last two years including:

- American President Lines intermodal terminal in Atlanta, GA
- Norfolk Southern intermodal terminal in Atlanta, GA
- Port of Houston, TX
- Port of Savannah, GA
- Port of Norfolk, VA
- Port of Charleston, SC

We are testing, at the Port of Charleston, results that we developed for analysing different stratagies for storing full containers before loading them on ships and when they are unloaded from ships. Our initial results indicate that the strategy of "block stacking", which is being increasingly used by U.S. ports to conserve space, actually requires more space that storing containers on chassis and is much more expensive in terms of handling cost. For the Port of Charleston, the estimated savings as a result of our effort is about $7,000,000 per year.

5 Papers published or accepted

- J. Bartholdi, III and D. Eisenstein. "A production line that balances itself", to appear in Operations Research.
- J. Bartholdi, III, L. Bunimovich, and D. Eisenstein. "Dynamics of 2- and 3-worker bucket brigade production lines", to appear in Operations Research.
- J. Bartholdi, III, D. Eisenstein, C. Jacobs-Blecha, and H. Ratliff. "Design of bucket brigade production lines", submitted.

- A. Ramudhin, A., J. Bartholdi, III, J. Calvin, J. Vande Vate, G. Weiss. "A probabilistic analysis of 2-machine flowshops", to appear in Operations Research.
- J. Bartholdi, III and W. Nulty. "Robust spatial searching with spacefilling curves", in Proceedings of the 6th International Symposium on Spatial Data Handling; Francis and Taylor, Publishers (1995).
- J. J. Bartholdi, III (1993). "An interactive program to balance assembly lines", International Journal of Production Research 31(10):2447-2461.
- S. V. Amiouny, J. J. Bartholdi III, and J. H. Vande Vate (1993). "Minimizing deflection and bending moment in a beam", Mechanics of Structures and Machines 21(2):167-184.
- J. J. Bartholdi, III, T. D. Seeley, C. A. Tovey, and J. H. Vande Vate (1993). "The pattern and effectiveness of forager allocation among food sources in honey bee colonies", Journal of Theoretical Biology 160:23–40.
- Hane, C. A. and H. D. Ratliff, "Sequencing inputs to multi-commodity pipelines," Annals of OR, vol 57, 1995
- Ramudhin, A. and H. D. Ratliff, "On the Complexity of the Process Shop," INFOR, , vol 32 no. 2, 1994
- Montreuil, B. and H. D. Ratliff, "Generating a Layout from a Design Skeleton," IIE Transactions, Vol 25, No 1, 1993.
- Barnhart, C. and H. D. Ratliff, "Intermodal Network Design," J. of Business Logistics, Vol 14, No 1, 1993.

6 Ph.D. students

- J. Goentzel, in process

  We are studying the intermodal network design problem. The focus is on the location and sizing of facilities when you wish to consolidate shipments at the facilities and ship to the users from a single source.

- P. Goldsman, in process.

  We are studying the "drop-and-swap" problem of how to assign drivers to trips so that the drivers finish each week sufficiently close to home. We have discussed this problem with Schneider Logistics and with J. B. Hunt Transport, who have offered their cooperation.

- G. Hunt, in process

  We are studying problems associated with scheduling and routing of intermodal carriers. The focus is on container ships but many of the problems are essentially the same in scheduling intermodal trains.

- C. Wratney, in process.

  We are studying the real-time routing of intermodal end-of-line pickups and deliveries. For this problem class, only a portion of the pickups and deliveries are known when the operation period begins. The remaining requirements come in as time goes on and have to be included in the work period.

- K. Gue; "Layout and design of LTL freight terminals", 1995. Assistant Professor, US Naval Postgraduate School

- S. Lapierre; "The Logistics of Preventive Health Services Using Fixed and Mobile Facilities", 1994. Assistant Professor, Université of Montreal

- W. Nulty, "Geometric searching with spacefilling curves", 1993. Vice-President for Engineering, CAPS Logistics.

- B. Stutzman; "Zone formation problems on embedded planar graphs" (1992). CAPS Logistics

- C. Hong; "An $O(n)$ planar network shortest path algorithm", 1993. Consolidated Freight

- C. Hane; "Scheduling multi-product pipelines" (1992). CAPS Logistics

7 Self-organizing logistics systems

Another effort, partially funded by AFOSR, has been directed toward realizing self-organizing logistics systems. In particular, we have devised a new way of coordinating workers who are picking items from a warehouse. Order-picking is labor-intensive and so managers want to keep all pickers busy. Standard practice is to attempt to balance the work by partitioning the warehouse into contiguous sections called "zones" and then restricting each picker to work within her zone.

Our idea is to define a protocol to be followed by each picker that results in dynamic zones that spontaneously adapt to the statistics of the order stream and the individual performance of the workers. The result is that work is constantly reallocated to improve balance and so the pick rate is significantly increased.

We suggest that the pickers work as a "bucket brigade": When the last picker completes an order, she pushes it onto the take-away conveyor and then returns to take over the order of her predecessor, who in turn takes over the order of her predecessor, and so on until the first picker begins a new order.

Pickers must maintain their sequence: No passing is allowed and so it can happen that a picker is blocked by her successor. In such case we require that she simply wait until her successor moves far enough down the aisle that she can resume picking.

We claim that sequencing the workers from slowest to fastest will maximize the average pick rate of the workers. We have gathered an array of evidence

including, mathematical analysis, simulation, and, most importantly, field experiment.

In February 1995 we implemented order-picking by bucket brigade at the Central Warehouse of Revco Drugstores, Inc. The most striking benefit of bucket brigade picking was an increase in pick rate exceeding 30%, which was achieved at no capital expense.

To help introduce this idea to retail warehousing (its most natural application) we have visited or talked with representatives of the following:

- Revco D. S., Inc., February, March, April, May, September 1995
- Big B Drugstores, June 1995
- Blockbuster Music, July 1995
- Eckerd, July 1995
- Walgreen's, August 1995